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A component based bottom-up building stock model for comprehensive environmental impact assessment and target control

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ABSTRACT

The building stock is one of the most important energy consumers worldwide. Therefore, a number of energy reduction targets and regulations exist for the construction sector. Different building stock models have been developed in order to investigate the potentials of energy-efficiency and changes in energy source in the building stock. However, these models often have important shortcomings, since they are single-issued and do not include the life cycle of buildings. Thus, we propose an innovative assessment methodology in the form of a life cycle-based building stock model (LC-Build). The building stock is clustered in building cohorts of similar construction and equipment characteristics in terms of type, construction period and building technology systems. The most important building components are assigned specific thermal transmittance values. Figures for diffusion and retrofit rate describe the development of the building stock fabric. Additionally, environmental impact from the energy supply side is taken into account. This approach facilitates the evaluation of the effectiveness of measures and their dynamics on the building stock, such as newer and more efficient technologies and practices related to energy policies and prices. Furthermore, the model has a direct relationship to the construction activity (energy-efficiency measures, substitution of fossil energy based heating systems) and fosters the comprehension of material flows, related environmental impact, and costs. The practicality of this approach is demonstrated by means of a case study in the city of Zurich in Switzerland. The results suggest that Zurich has a remarkable potential to reduce its greenhouse gas emissions from the building sector: 85% by 2050. The case study highlights the advantages of the proposed modeling approach. The LC-Build is a valuable tool to identify and test sustainable energy targets for building stocks, such as the European 20–20–20 target.

Contents

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1. Introduction

Worldwide, different visions for the abatement of anthropogenic climate change exist. For instance, the European Union (EU) agreed in 2008 on the so-called 20–20–20 targets [1]. This intermediate-range vision has three target criteria for the year 2020 (20% reduction of greenhouse gas emissions below 1990 levels, 20% share of renewable energies, 20% higher energy efficiency/20% lower primary energy use compared with projected levels). In December 2011, a follow-up road map was published, in which the European Union commits to a reduction of greenhouse gas emissions of 80 to 95% until the year 2050.

The residential building stock is responsible for 36% of total EU27 greenhouse gas emissions and ca. 25% of final energy demand [2,3]. In order to harness the buildings reduction potential, the EU Parliament amended the energy performance of buildings directive (EBPD) in 2010 with regulations postulating 'nearly zero energy buildings' by 2020 [4]. Since the European building stock has a relatively elevated average age and retrofit rates are lengthy, buildings have a considerable average energy demand of approximately 200 kWh/m^2 a for all end-uses [5]. Recent refurbishment projects prove the effectiveness of newly developed technologies and materials in the building sector. A number of reference projects prove the feasibility of reducing space heating demand of old residential buildings by a factor of 10 [6–9]. That corresponds to a reduction in greenhouse gas emission of approximately 75 kg of CO_2-equivalent (CO_2-eq.) per square meter per year [10]. Such figures illustrate that both new and existing buildings hold significant reduction potential.

Governments, building owners and other stakeholders have an interest in knowing the impact of efficiency measures on the building stock. On the one hand for reasons of financial planning, but on the other hand also in order to control their performance in terms of climate change visions, such as the 20–20–20 target. For this purpose, a number of models were developed in recent years. This paper gives an overview and proposes an enhanced approach, called (LC-Build), including additional parameters, compared to existing models.

In this first section, the paper gives an overview of common building stock modeling techniques and their use as an environmental impact and target control tool. Section 2 proposes a new method for building stock modeling by incorporating the life cycle approach, building components and energy supply sector (LC-Build). In Section 3, feasibility is demonstrated by means of a case study. Potentials and limitations of the approach are discussed in Section 4. Finally, conclusions and an outlook on future enhancements are given in Section 5.

1.1. Overview of modeling techniques

Swan and Ugursal [11] and also Kavgic et al. [12] provide valuable reviews of current residential building stock models. Both differentiate between top-down and bottom-up models and discuss shortcomings of each type. Pure top-down models are an interesting option to describe building stocks, especially when data availability is limited. However, these models are practically unable to investigate the impact of specific measures or technologies since they do not explicitly consider a system's constituents [11–13].

Bottom-up models consider individual houses or aggregates of a building stock. Swan and Ugursal [11] differentiate bottom-up models by their use in statistical and engineering models with further subgroups defined for each (cf. Fig. 2 in [11]). The common advantage of engineering bottom-up models over top-down approaches is their ability to model the energy demand of end uses and (new) technologies in detail. The most important disadvantage of non-statistical bottom-up models is the lack of consideration they give to occupant behavior. Recent studies show that occupant behavior and socio-economic factors have an important influence on residential energy demand [14,15]. Statistical bottom-up models try to overcome this limitation by means of regression analysis from recorded data, such as energy bills [11]. However, these models are also less suitable to investigate technological change.

Furthermore, Swan and Ugursal [11] differentiate engineering bottom-up models into 'distribution', 'archetype', and 'sample' types. The archetype approach uses reference buildings clustered according to certain characteristics to describe the building stock. This is especially useful when only aggregated data on the building stock is available.

1.2. Shortcomings of existing stock models

So far, final or useful energy demand is considered as an output parameter in most building stock models, with some models including greenhouse gas emissions as well (cf. Table 2 in [12]). However, energy demand and greenhouse gas emissions for building operation do not provide comprehensive information about the total ecological impact of buildings. In recent years, the methods of life cycle assessment (LCA) and material flow analysis (MFA) have become increasingly popular in the consideration of not only impacts due to operation but also overall environmental impact during the entire life cycle of a product. This is important because considerable parts of environmental impact often take place upstream or downstream of a process. For instance, compared to incandescent light bulbs, energy saving bulbs may consume less electrical energy during their service life. However, their greatest environmental impact might actually take place in the production and especially disposal phase of the product since they contain toxic material such as mercury. Hence, multi-criteria analysis and LCA-based indicators are also increasingly applied in typical energy sciences [16–21]. That approach allows for a broader view on the environmental impact of systems or technologies and construction activity.

Consideration of the entire lifetime of an energy efficiency measure in buildings is necessary to evaluate its factual effectiveness and payback. The reduction in energy demand for building operation represents only part of the environmental and economic impact. Transport, fabrication, fitting, usage and disposal of building components or systems may involve substantial impacts directly or within their upstream or downstream processes. Ramesh et al. [22] show that 10–20% of a building's primary energy use is due to embodied energy. This relative share

of embodied energy increases with lower space heating demand because the impact increases in relative terms and the amount of insulation material increases in absolute terms [23].

Thus, refurbishment expenditures should be offset by benefits due to energy saving within a useful period (i.e., at least within the lifetime of the equipment) in order to realize an overall environmental or economic benefit. If lifetime energy savings of the measure do not overcompensate the embodied impacts, the measure is ineffective from an ecological point of view.

Ardente et al. [19] look into the primary energy and greenhouse gas payback time of retrofit measures for a number of case studies. They determine the number of years in which annual heating energy savings compensate the primary energy and greenhouse gas expenditure due to construction activity and material. According to the authors' case studies, payback time varies greatly (between 0 to 32 years) depending on project and measure. Nemry et al. [24] go a step further and systematically assess the whole life cycle impact of 22 building types for six different environmental impact categories. By testing the effect of four different retrofitting measures, they determine the environment saving potential for those buildings and, by means of upscaling, for the EU-25 building stock. On the one hand, this kind of survey helps policymakers get a broader view of how to reach climate protection acts, such as the 20–20–20 targets. On the other hand, it gives an indication of possible rebounds.

Furthermore, the extent of environmental impact may strongly depend on the considered LCA indicator and system boundaries, since each indicator evaluates specific environmental issues. For example, CO_2-equivalent emissions describe the climate forcing effect of air emissions. However, it does not characterize impact on other environmental assets, such as air pollution eutrophication of waters, land/resource use, human toxicity, etc. Therefore, the system boundaries, allocation method, and indicators should be chosen according to the goal and scope of the respective study as the life cycle assessment methodology according to ISO 14 040 [25] suggests.

Current stock models investigate mostly (thermal) energy demand of buildings, yet do not specifically look into energy conversion and the supply system [12]. However, a considerable part of environmental impact takes place upstream in the energy supply chain, especially in the case of electricity. Supply technologies change over time and may develop as dynamically as the building stock does. For instance, the nuclear phase out in various countries around the world may or may not lead to a more CO_2-intense electricity mix in the future, depending on whether fossil-based power plants or renewable energies are used to fill the resulting supply gap. In addition, the building stock's thermal energy generation technologies may change considerably over time. New technologies, such as more efficient heat pumps, may result in lower fossil fuel demand and a shift towards electric energy demand. Moreover, heat pumps allow decoupling the energy supply of a building from the actual site to the electricity producers. That way dwelling owners or operators can take advantage of future addition of renewable energy generators into the electricity grid. Therefore, the energy supply side should also be included into a holistic building stock model that focuses on environmental impacts.

2. Methodology for a new building stock modeling approach

This paper proposes a framework for a next-generation building stock model, which overcomes some of the limitations mentioned previously. The aim is to offer a wider view on building stocks and facilitate the study of large-scale interrelationships of ecological and economic impacts caused by constructional and other measures. The model should include the following features:

- Simulate policy measures and technology-based scenarios
- Capability to determine environmental impacts on the basis of LCA indicators
- Include energy conversion and supply sector
- Consider building components and material flows
- Conform to local standards and building law
- Allow discussion with non-experts by using everyday/understandable parameters
- Work with limited input data
- Flexibility for future enhancements (occupant behavior, economy, etc.)

The aim is to develop a general framework for a building stock model that allows the study of the most important mechanisms within an existing building stock. This includes structural effects of construction activity such as new construction, refurbishment and demolition of buildings [26]. Another criterion is a direct relationship to building physics, i.e., building components. This allows one to look at material flows of building components and to relate them with construction costs and environmental impact. In order to investigate life cycle energy and total environmental impact, a relationship to the energy supply sector should be established. Since the lack of data is often a fundamental limitation for any kind of model, another priority is that the model should operate with incomplete and aggregated data.

In the following section, the paper introduces a theoretical approach on how to realize such a model. Section 3 will present a case study where the approach has been partially applied. The case study's most important novelty, in comparison to existing bottom-up models, is the component-based approach illustrated in Section 2.2.

2.1. Model structure

In order to investigate the impact of new technologies and policy scenarios on the building stock, the choice of a bottom-up model seems appropriate. The need for transparency (enabling review by non-experts), conformity to codes and standards, and a clear relationship to building physics suggests the use of archetype build-

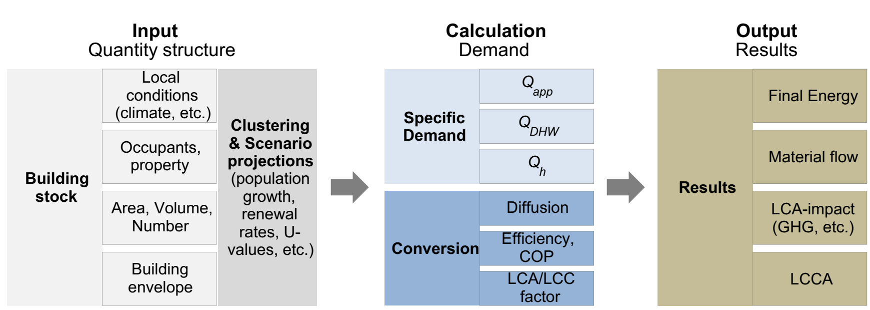

Fig. 1. Schematic model structure.

ings for describing the building stock. That means buildings with similar features, in terms of geometry, heat transfer coefficient (*U*-value), fabric, occupant type, etc., are clustered and represented by a reference building. Such common characteristics may be represented by, for example, occupancy type and construction period [27]. The limitations of typical engineering models (cf. Section 1.1) can be overcome by including statistical modeling techniques as proposed by Swan et al. [28–30]. They employ neuronal-network models for the end-uses of electrical appliances, lighting, and hot water production since the building's occupant primarily influences those. Aydinalp et al. [31] and Aydinalp and Ugursal [32] illustrate the advantages of this approach for these appliances. All other end-uses are modeled by means of an engineering bottom-up approach since they are mostly technology dependent.

The bottom-up model LC-Build introduced here calculates energy demand and translates it into environmental indicators. The temporal resolution (horizon and time steps) depends on the focus of the respective study. Fig. 1 illustrates the model's overall procedure. From left to right, data is processed and transferred to the next module. Each calculation step is carried out in one of four specific modules: quantities, specific demands, conversion factors, and (LCA/LCC) indicators and final results.

The determination of the quantity structure, which will serve as input data, is the first module (i.e., left-hand side in Fig. 1). General data for building simulation and building stock quality and quantity is collected at that point. This is comprised of weather data for the respective locations, diffusion of energy supply systems and appliances, thermal quality of building envelopes, etc. The building stock is described by data on occupancy characteristics such as building ownership, number of occupants, and vacancies, and by overall quantities such as number of households, building volume, and area. Subsequently, the data is processed and clustered, and projections for future development are made based on demographic projections, household size assumptions, diffusion rates and growth functions. This step is necessary in order to determine the future development of building stock.

In certain cases, data gaps can be filled by using average national data. For instance, if data on the number of households, heated floor space, etc. are not directly available, the module may calculate these values from average figures. Coefficients for building retrofit and demolition of heated floor space describe construction activity in the building stock (Eq. (1)). Either these figures apply to the entire building stock or certain segments can have individual rates.

$$A_{t,c} = A_{0,c} + \sum_{k=1}^{t} A_{k-1,c} \cdot r_{new,k,c} - \sum_{k=1}^{t} A_{k-1,c} \cdot r_{dem,k,c} \tag{1}$$

where, t is the calculation end year, k is the timestep, c is the building cohort, $A_{t,c}$ is the heated floor space of building cohort c at time t, $A_{0,c}$ is the heated floor space at starting year ($k=0$), $A_{k,c}$ is the heated floor space at timestep k, $r_{new,k,c}$ is the new construction rate, $r_{dem,k,c}$ is the demolition rate.

Eq. (1) example formula for heated floor space calculation.

The next and second module clusters data and generates figures for the future scenarios by applying projections and trend functions.

2.2. Demand

In the second step (i.e., depicted as 'Calculation' in Fig. 1), the model determines the specific demand (specific meaning related to a unity of the quantity structure, e.g., per square meter of heated floor area) of each end-use, such as space heating demand (Q_h), electrical household appliances (Q_{app}), and domestic hot water production (Q_{DHW}). Accordingly, this section is structured as follows: retrofit of building envelope, technology diffusion (ventilation and heating systems), and diffusion of household appliances.

2.2.1. Retrofit of building envelope

The modules for energy demand assessment should be based on generally accepted standards, such as EN ISO 13790 [33]. This means the level of detail of the archetype buildings needs to correspond to the requirements of the respective standards.

In order to facilitate the functionalities described above, we propose a new approach for modeling the building envelope. Each cohort of the building stock is described by an archetype that contains representative (average) building components for wall, window, roof, and floor. Data on dimensions (area, length of thermal bridges), orientation, thermal quality, as well as an annual retrofit rate is necessary to investigate measures (such as the addition of thermal insulation). By feeding the resulting building envelope into the space heating demand module, annual demand is determined. This novel approach allows the modeling of the evolution of the stock's energy demand over time ($Q_{h,c}(t)$) by using diffusion factors for describing retrofit quality and rate (cf. also next section). Hence the model allows one to investigate, for example, the effect of a new retrofit window type (having a lower *U*-value) penetrating the market.

The *U*-value describes a component's thermal quality after a successful renovation and therefore its energy losses. We introduced the figure 'effective retrofit rate', describing the share of thermally improved building components in a certain period of time (cf. Fig. 2). This means only measures such as the addition of insulation material have an influence on it. For instance, in the case a renovation consists only of maintenance repairs, it will not have an energy-efficiency impact and therefore does not apply. Should the renewal of a building component be successful (in terms of thermal resistance), renovation rate and *U*-value will describe its outcome on energy demand of the next time step.

Fig. 2 illustrates a possible development of *U*-values and renewal rates of the most important building components (regarding energetic performance of a building). On the left-hand side, a decrease in *U*-values takes place over time. Thus, in

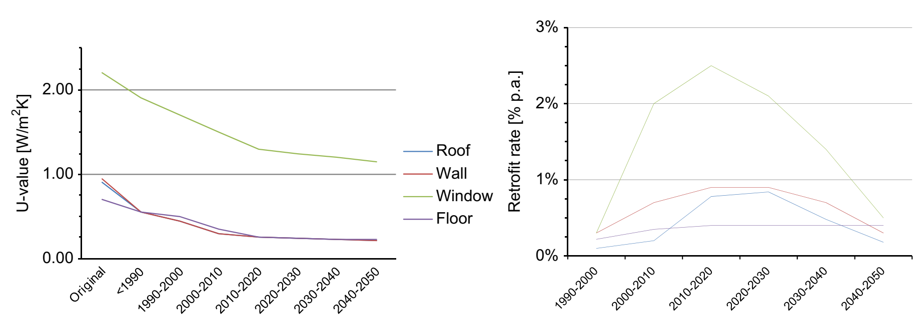

Fig. 2. Examples of *U*-value (left) and effective retrofit rate (right) for one building cohort 1976–1985 for one of the scenarios. Windows, wall, floor and roof [34].

this example, a future refurbishment of a building yields better *U*-values. That trend is due to an increased thickness of insulation as well as new materials and technologies that lead to improved thermal insulation of a building. This development is driven by autonomous techno-economic progress and policy instruments such as codes and standards, promotion programs including subsidies, etc. The right-hand side of Fig. 2 illustrates the retrofit cycles typically taking place in buildings. Since building materials have similar lifetimes, buildings of certain construction periods are likely to be refurbished in the same period. After a renewal cycle is completed, refurbishment of these buildings becomes less likely.

2.2.2. *Technology diffusion (ventilation and heating systems)*

As a result, figures describing penetration speed and extent of factors that influence energy demand are also necessary. Similar to the previous step, these modules compute technology diffusion rates based on the respective technology and its life cycle [35]. The technology diffusion rates, describing either the presence or distribution of a technology, may be based on different techniques, such as regression analysis. Rao and Kishore [36] provide a review of different technology diffusion models, which can potentially be applied here. Furthermore, they discuss possible approaches for economic model feedback and policy influence. For instance, the Bass model [37], described in Eq. (2), is a common formula for describing technology diffusion on markets and can be applied for this purpose. Higgins et al. [38] employ a similar approach for their stock model, using diffusion rates, based on the Bass model.

$$\frac{dN}{dt}\left[p+\frac{q}{m}(N(t))\right][m-N(t)] \quad (2)$$

where, $N(t)$ is the cumulative adoption at time t, p is the coefficient of innovation, q is the coefficient of imitation, m is the total potential.

Eq. (2) the Bass model describing the diffusion of a technology.

2.2.3. *Diffusion of household appliances*

McNeil and Letschert [39] describe a methodology to determine the diffusion of household appliances in the residential sector by taking, among others, macroeconomic drivers into account. Tao and Yu [40] and Schade et al., etc. [41] use similar methods to assess the future energy demand of household appliances. By combining this approach with specific energy demand, market diffusion rate, and product lifetime, future market distribution and household energy demand can be projected.

Fig. 3 provides an example for refrigerators in Zurich's households. The dashed grey line in the right-hand side figure illustrates overall ownership rate. Currently most households are equipped with this kind of appliance. However, it is expected that in the future ownership will increase above 100%, implying that some households have more than one refrigerator. The left-hand side figure illustrates the diffusion of the different energy efficiency classes, which will result in the demand curve illustrated by the red line in the right-hand side figure. In this example, it is expected that energy efficient devices will dominate refrigerator sales in the future and therefore average energy demand per household will decrease from approx. 225 kWh in 2005 to about 110 kWh in the year 2050. That means that in this case energy efficiency is able to overcompensate for the increased future ownership rate. The assumptions in Fig. 3 are based on a different household surveys carried out in Zurich, as published by Bush et al. [42].

2.3. *Energy conversion and supply*

After having calculated (useful) energy demand (i.e., Section 2.2), final energy demand and its break down on different energy carriers

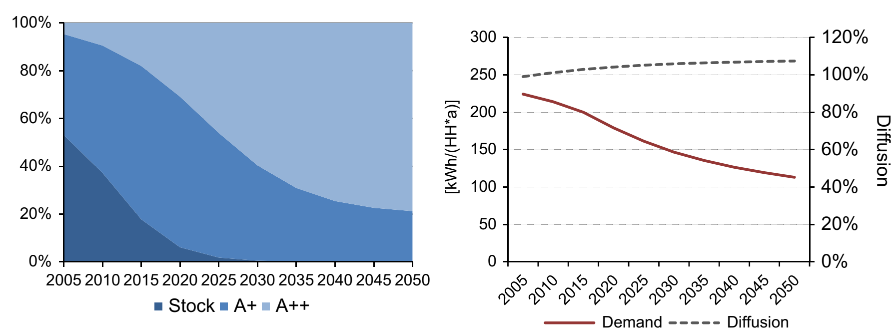

Fig. 3. Exemplary household distribution of refrigerators with different energy efficiency classes and its development over time (left) and total ownership rate and the resulting specific (average) household energy demand until 2050 (right).

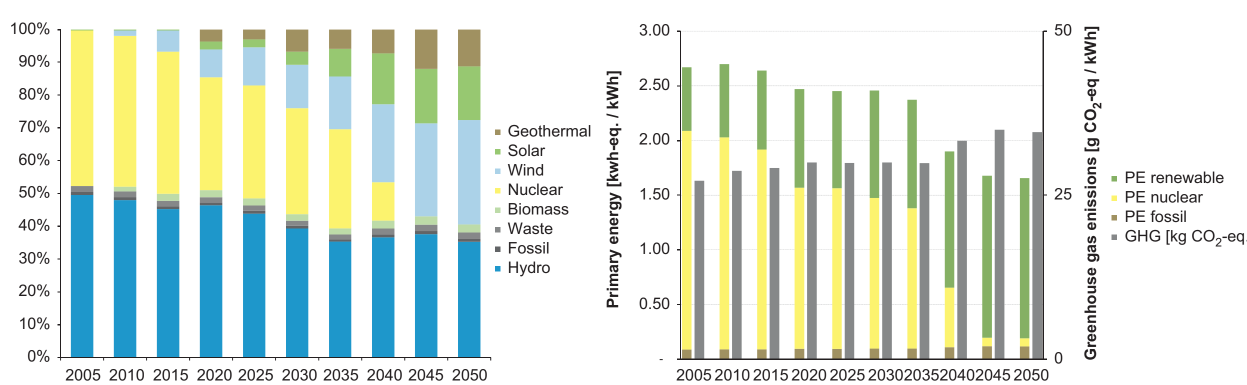

Fig. 4. Energy carrier distribution for electricity generation (left) and resulting impact factors (right) for Switzerland.

is modeled. The type of the buildings' energy supply system and its conversion efficiency ultimately determines final energy demand and environmental impact, such as greenhouse gas emissions. The future development of the heating system stock is modeled by means of exogenous assumptions regarding the market share of new and replaced buildings, as well as substitution processes. In the latter case typical lifespan for renewal and replacement rates are taken into account to prevent premature replacement. The supply structure is differentiated between thermal energy for domestic hot water and space heating.

Based on the results of the final energy demand by fuel type and electricity, the more upstream processes are taken into account, i.e., exploitation, refinery, district heat production, electricity generation and the transportation of the different energy sources. So far electricity production is typically centralized, and thus it is equal for all building types and ages. Data from national energy statistics and power generation forecast studies serve as the basis for determining environmental impact. Fig. 4 illustrates this process. In this example, data was used from the official energy outlook of the Swiss Federal Office for Energy (scenario IV, E) [43]. The scenario, shown in Fig. 4, represents a scenario in which run-out nuclear power plants will not be replaced with new ones and the resulting supply gap is filled by renewable energies such as wind and geothermal (cf. also Section 3.2 and Fig. 5). Since Switzerland has only four active nuclear power plants, their phase-out shows a direct effect in Fig. 4.

Electric power generation implies emission of greenhouse gases and consumption of primary energy resources. Each energy carrier (left-hand graph of Fig. 4) is weighted by its corresponding conversion factor in order to give an average factor for electricity for each time step (and right-hand graph of Fig. 4). According to data in ecoinvent [44], the conversion factors for the LCA assessment are based on final energy demand and therefore environmental impact is calculated from this (cf. Section 2.4). For further detail on impact of electricity mix, refer also to the case study in Section 3.

In order to determine final energy demand and LCA-results for domestic hot water and space heating, the model determines energy conversion factors based on energy carrier diffusion. Each cohort and end-use has its proper energy carrier distribution. Changes in energy supply over time are also described by diffusion rates. Specific demand, efficiency factor, and quantity (all calculated in the earlier steps) result in final energy demand of the respective end-use.

2.4. Including the life cycle

As illustrated in Section 1.2, energy demand as a single-issue indicator may deliver insufficient evidence of the usefulness of a measure. Energy carrier distribution also plays an important role in determining environmental impacts for conversion technologies. The provision of energy implies a process for energy extraction, infrastructure, transport, etc. These can be integrated by consulting life cycle databases, such as ecoinvent [44,45]. They contain information on typical environmental impacts occurring in upstream processes. For instance, the combustion of 1 kWh of fuel gas implies not only 203 g of direct CO_2-eq. emissions, but also 38 g CO_2-eq. (16%, respectively) being caused by remote processes.[1] Furthermore other midpoint or endpoint LCA-indicators, such as ReCiPe [46], etc., can be employed to characterize environmental impact due to energy consumption.

An important advantage of the component-based approach, as described above, is the possibility to estimate material flow of construction materials. By means of diffusion rates for building components and assumptions about the components used, mass flows can be deduced. The dimensions of the archetype buildings represent average building envelope surface areas of their corresponding cohorts. Along with the diffusion rate, the annual amount of treated surfaces can be determined. That allows on the one hand for an evaluation of environmental impact and costs, and thus on the other hand for the opportunity to verify the plausibility of the assumptions. For instance, the local construction industry's capacity to refurbish buildings can be compared with the required refurbished surface area.

2.5. Model use

In order to investigate the effect of measures on the current and future building stock, scenarios with different input parameters can be used. Using a business-as-usual scenario helps to differentiate 'naturally' occurring effects in the building stock, such as population growth from forced development due to policy measures, etc.

The different scenarios may include either variations of single parameters or sets of different assumptions. A sensitivity analysis or impact assessment of certain policies mostly affects only individual parameters. An example would be the survey of a forced stock renewal strategy. That is, buildings are demolished and substituted rather than renovated. Using different sets of parameters may reflect certain policies, such as a low carbon-oriented governmental strategy.

Nevertheless, model operation is an iterative process where the model actually may be a tool to test the plausibility of certain assumptions or a tool for illustrating and discussing input data and its effect.

3. Case study

In the following section, a case study on the city of Zurich is presented. This first version of the model (LC-Build 1.0) implements a series of the methodology described in the previous section. Emphasis was placed specifically on incorporating the component-based approach and the integration of the energy supply. Some of the functionalities, such as the integration of embodied energy of building components, were not fully implemented yet and will be part of a future version. The first version of LC-Build is based on a project commissioned by the city of Zurich in 2010 [34]. The aim of the project was to investigate the feasibility of a sustainable energy vision, called the 2000-Watt society.

3.1. 2000 W—The Swiss way

In 2008, the citizens of Zurich amended their community energy act with the obligation to respect the objectives of the 2000-Watt society by 2050. This means that by 2050 total primary energy demand must be no more than 3500 W per person, while only 2000 W may be produced from non-renewable fuels [47,48].[2] Therefore, a significant reduction of demand in all fields of everyday life (i.e., transport, offices, residential, etc.) is necessary. The intermediate goal (2050) for greenhouse gas emissions is set at 2.0 t CO_2-eq. per person

[1] Calculated form the process 'Natural gas, burned in gas turbine/GLO' in ecoinvent 2.2.

[2] 2000 W refer to a continuous power during one year which is equivalent to an amount of primary energy of 17,520 kWh per annum.

[48,49]. Given the present primary energy demand of 6300 W per person and a per capita greenhouse gas emission of 8.7 t CO_2-eq., this target appears ambitious. Compared to 2005 levels, primary energy demand needs to be reduced by 44% and greenhouse gas emissions by 77%. The goal is to investigate the building stock's contribution to such a sustainability target by means of the LC-Build model.

3.2. Model

In order to investigate the reduction timeline, the model was set for 5-year calculation time steps, ranging from the year 2005 to 2050. The building stock is clustered into 13 construction periods (CP) according to their year of construction. CP 1 to 4 describe the building stock existing in 2005. The data is based on a study investigating the future development of the Swiss building stock [50]. Partitioning the building stock into 13 construction periods (cohorts) corresponds to groups of buildings with similar construction details, such as component composition and form factor. The future construction periods, CP 5 to 13, describe the buildings erected or substituted from 2005 to 2050, each one spanning a period of five years.

The algorithm determining space heating demand is based on the current Swiss norm on thermal energy demand in buildings SN 520 380/1 [51], which is compliant to EN 13790 [33]. This means the space heating demand model does a monthly stationary energy balance for each building type, construction period (cohort), retrofit stage, and time step.

Retrofit rates are derived from Jakob et al. [52] who conducted a survey of approximately 2000 single- and multi-family buildings to inquire about the renewal behavior of house owners, differentiating by construction elements. Furthermore, the model makes use of various data published in earlier works. The most important source is the official energy scenarios by the Swiss Federal Office for Energy (SFOE) [53]. Moreover, the city's authorities and city-owned energy suppliers provided structural data, such as heated floor space, population, and energy carrier diffusion.

The initial distribution of thermal energy supply systems is based on statistical census data. The projection involves political scenarios, assumptions, and plausibility considerations by the authors and an expert group, which comprises representatives from the city's construction, energy, and environmental department. Furthermore, each energy carrier has a specific system-wide energy conversion factor, which also changes over time. The resulting output is final energy (in Petajoules) by energy type, which is an important figure for comparing the results to official energy statistics and calibrating the model.

The conversion factors, necessary for calculating primary energy and greenhouse gas emissions, are based on the life cycle inventory (LCI) database ecoinvent [45,54]. Based on energy carrier diffusion, a separate module calculates conversion factors for electricity and thermal energy converters, including the city's district heat facilities (cf. Fig. 5). For each time step, the sub-module weighs the prospected energy sources in order to give an average primary energy factor for each end-use.

The dynamics and interactions within the model were mostly achieved by means of exogenic definition of the various datasets. This means that the expert group together with the project team defined data on the development of parameters over time. Hence, parameters on the development of building stock, such as distribution of energy carriers, etc. is defined in an iterative process. In a number of project meetings, this group discussed the various possibilities and speed of different systems penetrating the Swiss market, their limitations, and possible rebound effects.

In order to identify the potential degree of influence on the one hand and to pinpoint the effect of particular measures on the other hand, the project team defined different key scenarios and sensitivities. A typical business-as-usual scenario (R1) describes the current development in the Swiss market/society concerning construction activity, heat generation systems, etc. Two efficiency scenarios describe ambitious changes in the building sector by 2050 (E1 and E2). Not only does efficiency of energy conversion improve considerably, but a significant switch in fuel types, from gas and oil towards renewable resources (such as environmental energy by means of heat pumps) also takes place. Table 1 illustrates the most important assumptions of the respective scenarios.

Moreover, the model differentiates between two electricity mix scenarios. Fig. 5 illustrates the two scenarios, which both closely follow the assumptions made by Zurich's electricity provider [55]. Scenario 1 (left-hand side) corresponds to a business-as-usual scenario and describes the continuation of former policy. That includes participation in new nuclear power projects after shutdown of current power plants in 2025. The result is a mostly constant factor for primary energy and greenhouse gas emissions.

Scenario 2 (right-hand side) describes a geothermal-oriented scenario [56]. Renewable energies (i.e., wind, solar thermal and geothermal energy) play a key role in replacing the current share of nuclear power. In 2050, only a marginal percentage of non-renewable resources for electricity production should remain (mostly due to electricity mix of the upstream processes in ecoinvent). Specifically, these are electricity from waste incineration plants and decentralized cogeneration fossil-fuel plants [57,58]. Accordingly, the primary energy and greenhouse gas factors change over time. The share in nuclear energy reduces significantly, and the renewable part substitutes most of its former share (cf. Fig. 5, right-hand side). The total primary energy factor decreases as well since the conversion of renewable energies is more primary energy efficient compared to nuclear power plants [54]. However, the phase-out of nuclear energy does result in an increased greenhouse gas emission factor (red line in Fig. 5). According to ecoinvent [44,54], nuclear energy causes very low greenhouse gas emissions (also compared to several renewable technologies, such as energy from solar, wind and biomass). Thus, its substitution by other technologies causes increased GHG emissions, but overall remain on a very low level.

Table 1
Comparison of the key assumptions of the reference scenario (R1) and the two variants of the efficiency scenario (E1 and E2).

	Reference year 2005	**Reference scenario R1 2050**	**Efficiency scenario EE1 & EE2 2050**
Energy conversion efficiency	ca. 85% overall efficiency	Moderate efficiency increase	ca. 12% increase
Energy carrier diffusion	ca. 80% oil and gas	ca. 60% oil and gas remaining 2050	ca.70% heat pumps, solar ca. 10% oil and gas remaining
Retrofit quality	n/a	Weighted average: 0.22 W/m^2 K	Weighted average: 0.14 W/m^2 K
Retrofit rate 2005–2050	n/a	Weighted average: 0.65% p.a.	Weighted average: 0.92% p.a.
Space heating demand	ca. 400 MJ/m^2 a	ca. 270 MJ/m^2 a	ca. 210 MJ/m^2 a
Electric appliances	Inefficient devices	Standard appliances (typically A)	Efficient appliances (typically A+)

The model allows one to individually combine key building sector scenarios with electricity scenarios in order to investigate interactions between the two. Thus, two efficiency scenarios exist: E1 and E2 corresponding to use of electricity mix 1 and 2. Moreover, the project team was interested in the impact of single assumption sets. Thus, it defined two sensitivities: exposing the impact of (a) the building envelope (i.e., reduced thermal losses of buildings) and (b) change in energy source (i.e., substitution of heating systems). The former is also outlined in a paper by Heeren et al. [59].

3.3. Results

The result vectors for this project are predominantly final energy in *MJ*, primary energy in *MJ-equivalent* [54], and greenhouse gas emissions in *kg CO_2-equivalent* [10,54]. In order to compare the results with the scope of a 2000-Watt society, they are also expressed as a continuous power (Watt per person, W/P) and, alternatively, as per capita greenhouse gas emissions (kg CO_2-eq./P) by 2050. Furthermore, the model calculates the results for each energy carrier, building type and, in an aggregated form, for a number of applications. Fig. 6 illustrates the primary energy results of the two main scenarios (i.e., Reference scenario in combination with the business as usual electricity mix (left) and Efficiency Scenario E2 with electricity from mostly renewable energies (right). In the Reference scenario, demand appears to be decreasing only slightly from 2005 to 2050. However, during that period the heated floor space increases by approximately 18% due to increased per capita dwelling area and considerable population growth in the city of Zurich. This is reason *per capita* primary energy usage decreases more than absolute primary energy demand and also the reason for the reduction in the R1 scenario.

Furthermore, Fig. 6 provides information on the share of renewable (primary) energy. In the baseline scenario, it amounts to 11% of the total in 2005 and increases to 25% in 2050. In contrast, the efficiency scenario in 2050 provides 80% of the necessary primary energy from renewable resources, which corresponds to a reduction of non-renewable primary energy consumption of 90%. By 2050, the total primary energy demand reduces by 19% in the baseline scenario and by 56% in the efficiency scenario (E2). This illustrates that the efficiency scenario E2 does not only imply significant reduction in energy demand by means of energy efficiency but also an important fuel switch to renewable energy sources (including electricity).

Since it is mostly the share of fossil fuels which is decreasing, this has an important effect on per capita greenhouse gas emissions. Fig. 7 illustrates the decline until 2050 in both scenarios. Compared to 2005, the per capita emissions in 2050 are cut back by 1.3 t CO_2-eq./P in the baseline scenario and alternatively by 2.4 t CO_2-eq./P in the efficiency scenario. Table 2 summarizes these results.

3.3.1. Scenario impact

Measures acting on the building stock's energy demand, or greenhouse gas emissions as the case may be, can generally be divided into two categories. The first category includes measures that attempt to reduce a building's energy *demand* by means of efficiency measures. In terms of the building stock, this could be, for example, an improvement of the building's envelope or heat recovery from exhaust air, etc. The second category is comprised of measures that make it possible to *supply* buildings with energy produced from

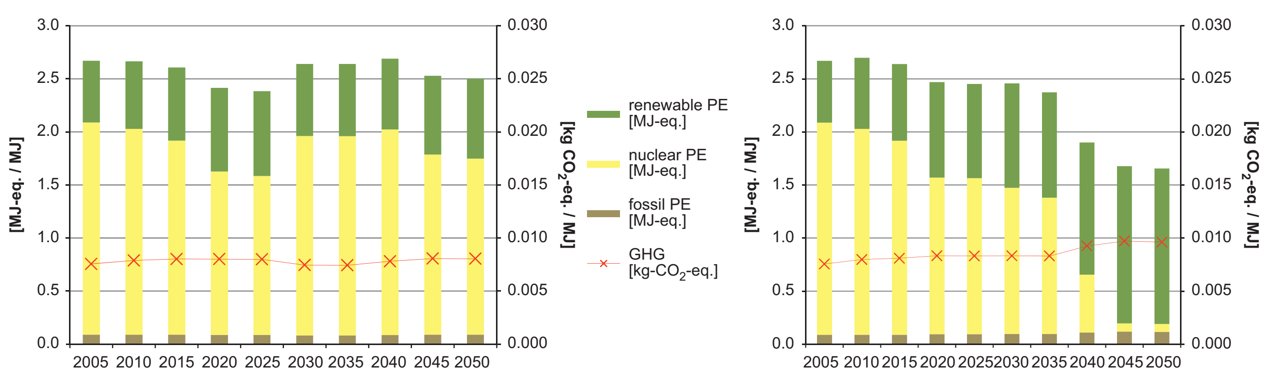

Fig. 5. Primary energy factors (green, yellow, brown) and greenhouse gas emissions (red, secondary axis) of Zurich's electricity production mix 2005 to 2050. Reference (left) and efficiency (right) scenario [34,55]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

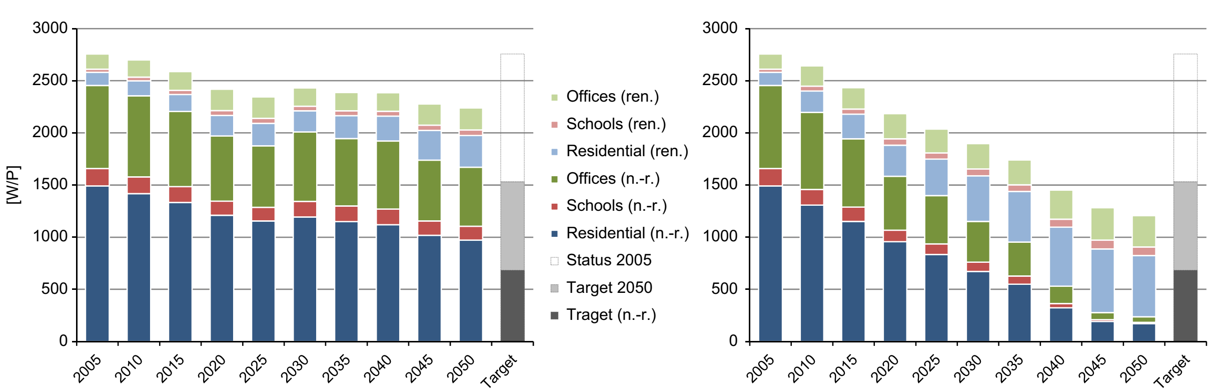

Fig. 6. Renewable (ren.) and non-renewable (*n.−r.*) primary energy demand [W/P] and 2000-Watt targets (grey bars); Baseline scenario R1 (left); Efficiency scenario E2 (right) [34].

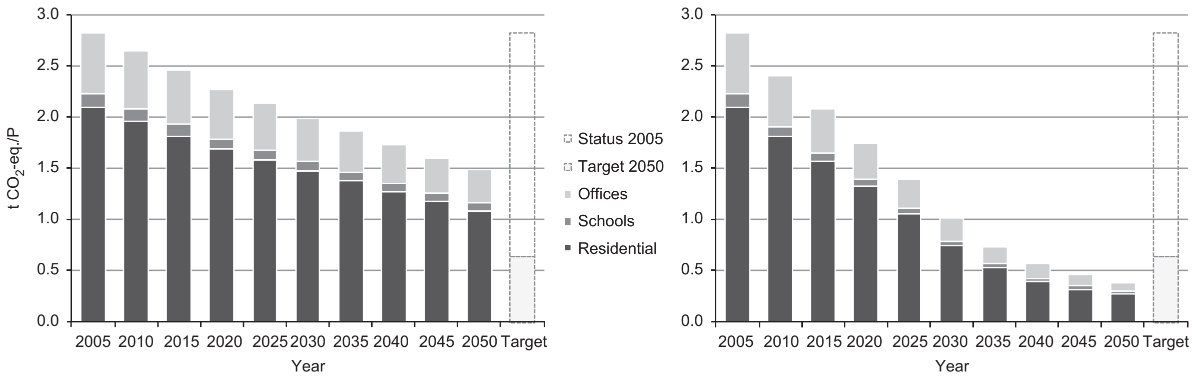

Fig. 7. Per capita greenhouse gas emissions [t CO_2-eq./P]; Baseline Scenario (left); Efficiency scenario E2 (right).

Table 2
Reduction in regard to primary energy consumption and greenhouse gas emission according to scenario (total value and relative reduction compared to 2005 in parentheses).

Criterion	Overall 2000-Watt society		Model Zurich (LC-Build)		
	2005	Target 2050	2005	Scenario 2050	
				Reference R1[a]	Efficiency E2[a]
Total primary energy [W/P][b]	6300	3500 (−44%)	2762	2243 (−19%)	1208 (−56%)
Non-renewable primary energy [W/P]	5800	2000 (−66%)[c]	1671	1671 (−32%)	237 (−90%)
GHG emissions [t CO_2-eq./P][b]	8.7	2.0 (−77%)	2.8	1.5 (−47%)	0.4 (−86%)

[a] Results from [34].
[b] As in [49].
[c] Assumption by the authors.

renewable resources and/or by more efficient energy converters. That could mean, for example, changing the energy source of a building from fuel oil to ambient or waste heat by means of a heat pump or a combined heat and power plant (CHP) [60,61]. Each strategy has a different effectiveness concerning reduction potential.

A. Reducing *energy demand* affects all indicators (primary energy demand, greenhouse gas emissions, share of renewable energy usage). However, due to differing flexibility within the demand categories (i.e., appliances, heating, etc.), a relative shift from thermal energy towards electricity demand is likely to take place and therefore alter the respective impact. Further analysis in [34,59] of domestic buildings illustrates this effect: In the case that the LC-Build model only considers efficiency measures concerning building envelope, renewal rate, and ventilation systems, the reduction of primary energy demand (total: −20%, non-renewable: −33%) is not as extensive as for the greenhouse gas emissions (−51%).
B. Another sensitivity scenario in [34] investigates the change in *energy supply*. Only energy sources for space heating and hot water production (including district heating) of the efficiency scenario apply. Since it is mostly combustion of fossil fuels that cause greenhouse gas emissions, the share of non-renewable energy also decreases significantly (−52%). Such a setup yields an intense reduction in greenhouse gas emissions (−81%) but a less important impact on total primary energy demand (−14%).

3.3.2. *Electricity*

Electricity plays an increasingly important role for the building stock, since electric appliances and heat pumps are continuously gaining market share [5,62]. In 2009, approximately 24% of the final energy consumed in the EU27 was in the form of electrical energy, compared to 19% in 1990 [62]. The LC-Build model assumes in the efficiency scenario E2 that the share of electricity from the total final energy demand of Zurich's buildings increases from 30% in 2005 to 43% in 2050 [34]. That shifts the focus from environmental impacts due to thermal combustion in buildings towards electricity production.

The effect of electricity from nuclear energy becomes visible when comparing the two efficiency scenarios. Scenario E1 comprises a relatively stable portion of approximately 40% electricity from nuclear power plants until the year 2050. Scenario E2 substitutes the fade-out of nuclear energy with renewable energy. Since the production of electricity from nuclear sources has a comparatively low efficiency, its primary energy conversion factor is higher than for most energy carriers (cf. Fig. 5). This means the conversion factor for total primary energy is 4.1 MJ-eq./MJ (99.8% being from non-renewable energy), while, for instance, hydroelectric energy has a factor of 1.2 MJ-eq./MJ (with 3% non-renewable energy) [54]. Consequently, total primary energy demand reduces in scenario E1 (−36%) less, than compared to E2 (−50%). In contrast, nuclear energy produces little greenhouse gas emissions, having an emission factor of 8 g CO_2-eq./kWh [44].[3] Accordingly, scenario E1 in 2050 has 5% lower total greenhouse gas emissions than E2 [34].

3.3.3. *Target control*

At the moment, there is no common consensus within the concept of the 2000-Watt society in Switzerland for the building stock's designated reduction target regarding primary energy demand and greenhouse gas emissions. The 2000-Watt society as defined by Bébié et al. [49] aims at a reduction of primary

[3] Dataset 'Electricity, nuclear, at power plant/UCTE' from ecoinvent 2.2.

energy demand of 44% and greenhouse gas emissions of 77% by 2050 (cf. Table 2). Presumably, the building stock has a different elasticity in terms of energy demand reduction or fuel switch than other sectors, such as industry or transport [48,63]. Nevertheless, these values serve as a first approximation for a possible reduction target. Table 2, and also Figs. 6 and 7 (dashed grey bars), illustrate the corresponding reduction targets for the Swiss building stock.

Table 2 illustrates that only the more ambitious efficiency scenario is able to meet the relative reduction targets through primary energy demand, alternatively greenhouse gas emissions. This shows that mere structural changes within the population/building stock do not suffice in order to comply with the 2000-Watt society. It is necessary to undertake further efforts regarding energy demand reduction and energy provision for the building stock. Yet, it seems feasible to adapt the building stock to the targets of the 2000-Watt society.

4. Discussion

The efficiency scenario does fully meet (and even exceed) the required reduction targets. Due to the urban setting, the city of Zurich holds a low share of industrial buildings and a large number of multi-family houses. Furthermore, the city has sound access to renewable energy sources such as running waters and waste heat. However, this result is also a consequence of underlying assumptions and hypothesis, and it therefore needs to be considered carefully. The results of the case allow for the following conclusions according to the achievability of the 2000-Watt vision:

1. Structural changes help to comply with the 2000-Watt targets but do not suffice.
2. Efficiency scenarios suggest feasibility of reaching the target.
3. Combined measures on building envelope and energy supply are necessary.
4. Electricity mix has an important impact and affects mostly primary energy demand.
5. Buildings are unlikely to compensate insufficient reductions in other sectors (e.g., industry).
6. Measures on energy demand are more effective on primary energy demand.
7. Measures on energy supply are more effective on greenhouse gas emissions.

This paper proposes a general methodology for building stock models to represent building fabric in more detail and include life cycle environmental impact. The case study above illustrates its fitness for one specific building stock, however, the approach is transferable to other building stocks. Existing key issues are the availability of data on building envelopes and the retrofit rate.

As illustrated in Section 1.2, the field of environmental construction has a tendency to consider not only the operational energy demand of buildings but also environmental impacts across the entire life cycle of buildings [18,19]. This includes life cycle assessment (LCA) of building energy systems [64] as well as building structure [65]. Heeren and Wallbaum [23] show that the model is also suitable to process additional indicators, such as the method of ecological scarcity, used in LCA [66].

The number of building stock models [11,12] illustrates the great interest that exists in the building stock and especially in its reduction potentials. However, most models consider only energy demand and/or CO_2 emissions [12]. LC-Build focuses on, among others, the interactions of environmental impact and the construction activity in the building stock. The further development of this approach is intended to be a part of future work.

Retrofit rates for building components and appliance and heating system diffusion in the case study are estimated by expert teams and verified by the project team. However, this approach is time consuming and does not provide direct feedback. Therefore, it cannot be automated or integrated into other models. An additional module providing the economic and physical flows due to retrofitting would allow investigation of feasibility in terms of the economy and construction industry. Such verification is helpful, for instance, when a high retrofit rate might exceed the capacity of the economy to afford high-quality insulation material. In addition, the construction industry may have difficulties providing the required material or skilled workers. An economy module would also allow integration of the LC-Build into broader scale models, investigating other energy consuming sectors such as transport and agriculture.

5. Conclusion and outlook

The case study in Section 3 and the project reports [34,59,67,68] show that LC-Build is an adequate model to investigate specific questions, such as the 2000-Watt society, outlined in Section 2. The model provides primary energy demand and GHG-emissions for different scenarios and a 45-year timeframe while specifically considering the respective building stock characteristics. Thus, the model facilitates an evaluation of the building stock's future development. With this knowledge, policy makers and other stakeholders have at their disposal an important tool to investigate potentials of and measures acting on the respective building stock.

This type of target control is especially important when investigating energy or environmental targets, such as the European 20–20–20 target or the 2000-Watt society. In the case of Zurich and Switzerland, for example, it remains questionable whether the Swiss building stock will be able to make a sufficient contribution towards a 2000-Watt society [34,67]. Section 3 shows that the city of Zurich should consider action on both energy efficiency as well as renewable energies in order to comply with a 2000-Watt society (cf. Section 3.3). Structural and demographic changes taking place in the city help with achieving such goals.

Therefore, one conclusion may be that other sectors, such as industry or transport, need to cut back their energy demand even above the principle reduction targets given in Table 2. Consequently, the next step is the study of the relationships between the different demand sectors by means of a meta-study or model in order to identify their interrelationship and corresponding flexibilities. The LC-Build model is a useful tool to determine the demand of the building sector. In the future, it may be combined with other bottom-up tools in order to gain further insight into the interdependencies and the respective potentials.

LC-Build can be used as a tool to investigate the effect of specific measures. In two earlier publications [59,68] the authors isolate specific measures in order to determine the effectiveness of specific policy measures. For instance, the findings in [59] suggest that limiting the floor area per person to 70 m^2 could yield in a saving of primary energy demand of 5% by 2050, compared to the business as usual scenario. By simplifying the model, it is possible to provide policy makers and building owners a relatively simple tool for scenario impact assessment. This requires the creation of a comprehensive interface and means of data input for users.

In a follow-up project by Jakob et al. [69] the LC-Build model will be enhanced to version 2.0. By means of GIS-integration of Zurich, the city will be clustered in supply and demand regions in order to increase the model's resolution. Subsequently, the region's

renewable energy potential will be identified and its maximal exploitation modeled with the help of the LC-Build. Results will be published in 2012. A similar approach is proposed by Angelis-Dimakis et al. [70] in order to promote environmental decision support systems.

As mentioned earlier, a number of enhancements to the LC-Build are possible. These can be differentiated into enhancements concerning

a. (input) data quality
b. modeling technique
c. methodological
d. functional
e. (output) indicators

Concerning the modeling technique, further aspects having an impact on energy demand of buildings will be included. For instance, the representation of social and economic rebound effects and economic market mechanisms is planned. Furthermore, the modeling methodology might be enhanced with sensitivity and robustness evaluation by means of Monte-Carlo analysis. Additional functionalities, such as a module to assess rebound effects due to efficiency gains in the construction industry could be integrated.

Building stock models are common tools to investigate the energy demand of buildings. However, current models are able to investigate only certain aspects of renewable and sustainable energy demand (i.e., usually only operational energy demand is considered). Important parts of the stock's energy consumption and potential remain untreated or hidden in the energy supply side or in the form of embodied energy. However, with buildings becoming more efficient in the future, the embodied energy may represent an important share of total primary energy demand and accordingly environmental impact (cf. Section 1.2 and Ramesh et al. [22]).

As illustrated in the previous section, inclusion of material flows and prices is useful in determining practicability of scenarios. The next generation of the LC-Build will comprise these parameters for the respective building components and appliances. In this way, the model will provide dynamic feedback on the respective construction/retrofit activity. In order to consider environmental impacts other than greenhouse gas emissions, we plan to integrate additional LCA-based indicators. The component-based design of the model facilitates deducing the magnitude of treated building surfaces. Thus, implications such as costs and embodied energy will be integrated.

The case study in Section 3 illustrates the model's suitability to answer specific questions concerning building stocks. The approach of using a building component-based model proves especially worthwhile since it works with real-world figures that can be easily understood and used for different kinds of data processing. For example, Heeren and Wallbaum [23] deduce the amount of embodied energy by means of the component renewal rate (cf. Section 2.2) and typical figures for construction work in renovation and new constructions [71,72]. Furthermore, they show that environmental impacts of embodied energy gains relative importance as the operating energy demand of buildings decreases. These kind of considerations help identify and understand ecological payback, e.g., due to excessive renovation activity. A similar method could be applied in order to investigate economic payback of construction activity (cf. Section 2.2).

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